



Ministry of Energy
Geological Survey of Israel

**Development of the Negev erosional craters
in superposed stream systems**

Amihai Sneh



Front cover: “**Conjectural inlet**”, **Ramon Crater**, ... (Morning hours gliding clouds...).



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Abstract

The lithostratigraphy and structure of the northern Negev fold belt allow development of erosional craters in superposed stream systems. They lack any inlets but they do have conjectural inlets in the form of wind gaps. The craters formation is contingent upon the presence of the highly erodible rock beds of the Hatira Formation within the geological section, as well as the overlying, friable, Hazeva Formation sandstone and clay rock cover, in which streams can easily incise downward

Content

1. Introduction
2. Friable lithologies in the folds` geological sections
3. Burial of the Negev folds by the friable Hazeva Formation rocks
4. Wind gaps - `Inlets by conjecture`
5. Stages in the evolution of the Negev craters
6. Superposed stream system in the Soreq Valley to the north of the Negev
7. Conclusions
8. Appendix: Erosional craters worldwide.
9. References

1. Introduction

Erosional craters are geomorphological features developing mainly in folded belts worldwide. Classical erosional craters in the northern and central Negev, Israel, the focal point of the present study, developed along the crest of three anticlines (Fig. 1): The bowl-shaped Hazera 'Small' Crater along the Hazera anticline, the bowl-shaped Hatira 'Big' Crater along the Hatira anticline and the feather-like Ramon 'Giant' Crater along the Ramon anticline. Their lithostratigraphic exposed sequence includes alternating hard rock units of dolostone and limestone and soft rock units of sandstone, chalk, marl and clay. Basic relevant are given in Table 1 (Hazera – T22; Hatira – T23; Ramon – T24, together with other 41 selected craters around the globe). Table 2 includes relevant lithostratigraphic data concerning the geological column exposed in the Negev craters; the structural relations for two of them is demonstrated in three cross sections, Fig. 2 a-c. Fourteen, Google-Earth (GE) images of various craters were selected for presentation including those of the Hazera (GE1), Hatira (GE2) and Ramon (GE3).

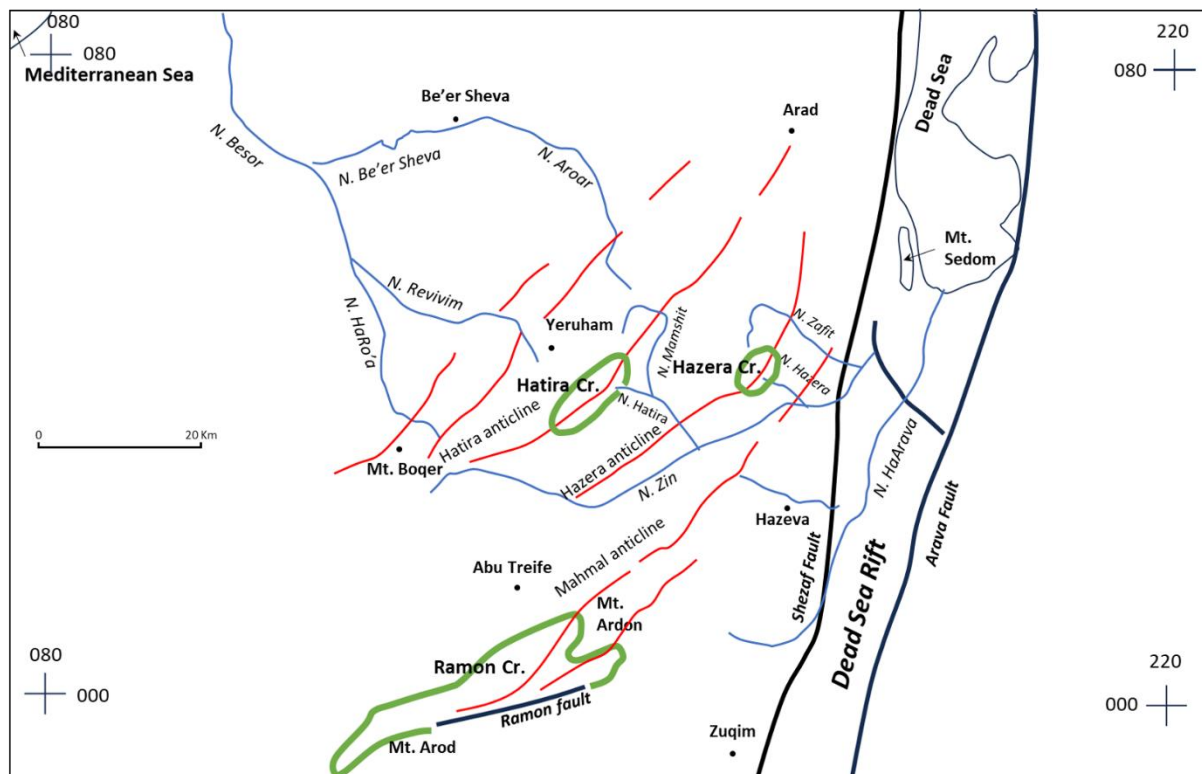


Fig. 1. Negev structures, streams and erosional craters. Geological structures after Sneh and Weinberger (2014).

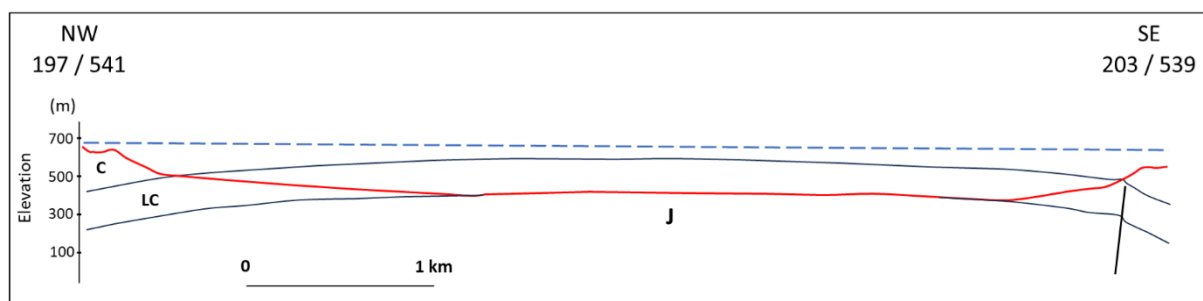
Number	Name	Country	Lat	Long	Size (km)	Relief (m.)	Remarks
1	Everett	USA PA	38°50'	78°25'	37x6	300	
2	Oval	USA PA	41°09'	77°10'	17x7	250	
3	Buffalo Mills	USA PA	39°56'	78°38'	21x2.5	300	
4	Burkes Garden	USA VA	37°06'	81°20'	15x7	150-450	
5	Paradox	USA CO	38°19'	108°51'	42x8	600	
6	Sinbad	USA CO	38°30'	109°00'	13x6	800	
7	Devils Pocket	USA MO	46°19'	109°42'	2.5x2.5	60	
8	Borregas	MEXICO CO	27°25'	101°24'	25x7	450	
9	Salinas Victoria	MEXICO NL	22°55'	100°30'	20x4	700	
10	Lavelanet	FRANCE	42°56'	01°52'	18x3	200	
11	Gex	FRANCE	46°21'	06°01'	6x3	900	
12	Court	SWITZERLAND	47°15'	07°21'	2x2	500	
13	Moutier	SWITZERLAND	47°17'	07°23'	1x0.8	400	
14	Tisslite Douchen	MOROCCO	30°38'	07°06'	6x3	200	syncline
15	Inlioua west	MOROCCO	29°24'	08°34'	30X10	300	
16	Bni Ykhlef	MOROCCO	32°44'	07°56'	18x4	150	syncline
17	Talbanine	MOROCCO	31°30'	07°32'	13x5	150	syncline
18	Tassoufante	MOROCCO	32°18'	04°47'	9x4	230	syncline
19	El Haouita	ALGERIA	33°41'	02°25'	20x6	40-80	
20	In Salah, Sahara	ALGERIA	26°16'	02°18'	9x7	30	
21	Gebel Hallal	EGYPT, SINAI	30°37'	34°04'	7x6	300	
22	Hazera	ISRAEL	30°57'	35°12'	7x5	350	
23	Hatira	ISRAEL	30°57'	35°01'	13x6	300	
24	Ramon	ISRAEL	30°35'	34°48'	41x9	350	
25	Har Arif	ISRAEL	30°25'	34°44'	1.5x0.7	200	
26	Sinjar	IRAQ	36°22'	41°41'	15x3	100	
27	Maroo	IRAN	27°26'	55°51'	20x5	300	syncline
28	Nowdan	IRAN	29°46'	51°35'	8x6	700	
29	Tang e Leylam	IRAN	32°59'	47°52'	4x3	900	
30	Dishmok	IRAN	31°20'	50°18'	6x4	1000	
31	Hajj Qalandar	IRAN	30°13'	51°11'	6x3	700	
32	Abdan Baghan	IRAN	28°08'	51°48'	3x3	150	
33	Anguran Salt Dome	IRAN	27°17'	55°52'	10x6	600	
34	Bela	PAKISTAN	65°57'	26°06'	40x25	600	syncline
35	Pir Zinda Sahib	PAKISTAN	30°25'	70°32'	50x5	200-400	
36	Ormara	PAKISTAN	25°28'	64°51'	40x15	N800 - S60	syncline
37	Qadzi Kalay (Urgun)	AFGHANISTAN	32°58'	69°02'	15x3	100	syncline
38	Kurmi	RUSSIA	42°28'	47°02'	5x5	1000	
39	Sakon Nakhon	THAILAND	17°13'	103°32'	13x5	150	
40	Kuchinarai	THAILAND	16°42'	104°04'	32x15	240	
41	Owen Springs	AUSTRALIA	24°00'	133°25'	43x6	100	
42	Finke River	AUSTRALIA	24°08'	132°49'	30x5	200	
43	Wilpena	AUSTRALIA	31°34'	138°35'	17x9	200-500	syncline
44	Chellala	ALGERIA	33°12'	0°07'	5x2	300	

Table 1. Erosional craters worldwide - basic data

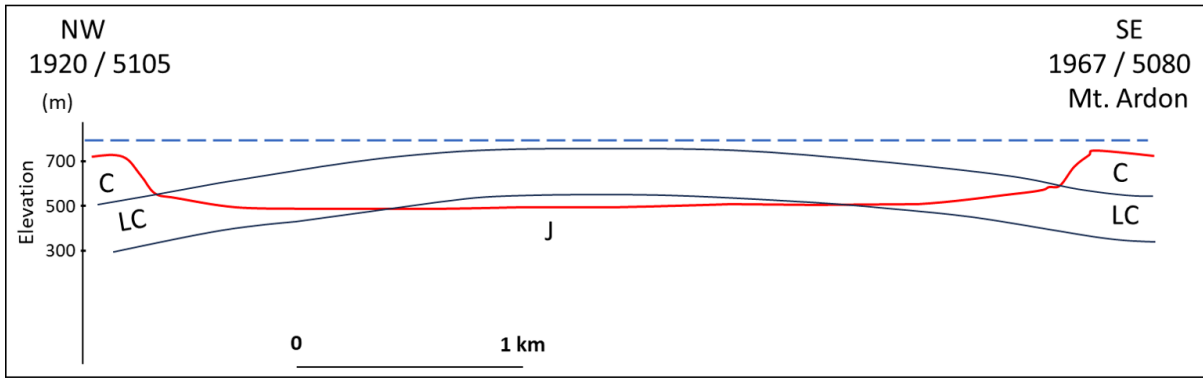
Age	Group	Formation	Lithology	Thickness (m)
Plio-Pleistocene	Dead Sea	Hufeira - Arava	S.st, Cgl.	30 - 90
Miocene	Saqiye	Hazeva	S.st, Cgl., Clay	230+
Up. Eocene - Oligocene	Saqiye	Qeziot – Har Aqrab	L`st., Marl	300
Eocene	Avedat	Mor - Matred	Ch., L`st,	150 - 180
Senonian - Paleocene	Mt. Scopus	Menuha - Taqiye	Ch., Chert, Marl	140 - 220
Albian - Turonian	Judea	Hevyon - Zihor	Dol., L`st, Marl	410 - 500
Early Cretaceous	Kurnub	Hatira	S`st., Volc.	200
Jurassic	Arad	Ardon - Mahmal	L`st	40 - 70
Triassic	Ramon	Gevanim - Muhila	L`st., Gyp., S`st	65 -165

Table 2. Stratigraphic sequence exposed in the Negev craters and vicinity.

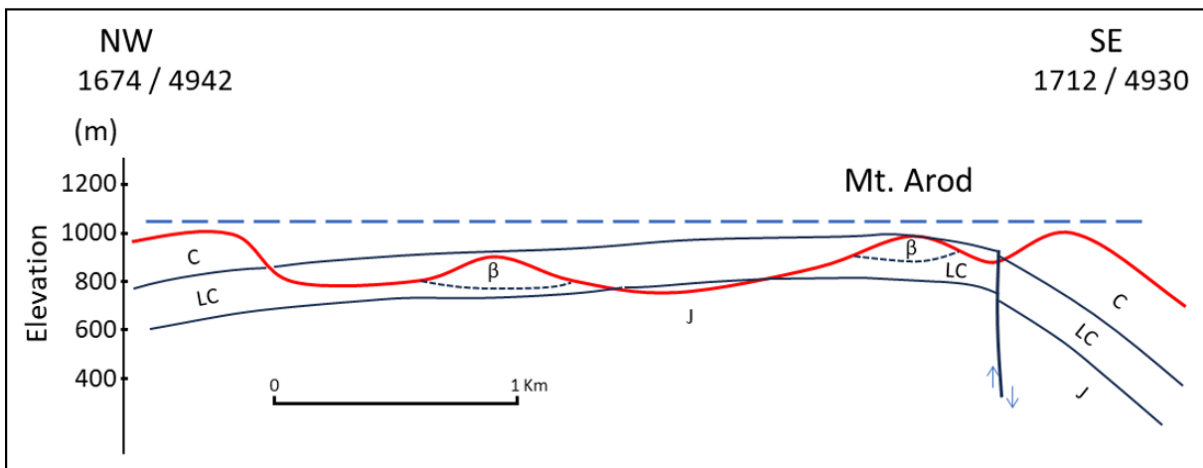
Fig. 2. Sections across the Negev erosional craters, prepared on the basis of geological maps by Roded (1978), Roded (1996), Avni et al., (2016), Avni (2001) and Avni et al., (2017). The cross sections display present-day structural position and topography and not their state during the Neogene. They were designed to display as little discrepancy as possible between present day and the past. Denudation surface - Dashed line - is drawn as a horizontal line, slightly raised to allow vertical lowering of the rims by erosion since the end of the Miocene. J – Jurassic formations. LC – Lower Cretaceous formations. C – Albian, Cenomanian and Turonian formations. β – basalt. Note that strata were ripped off from the top of structures above the denudation surface, and contrary to other views, e.g., Zilberman (2000), Lower Cretaceous, Hatira Formation sandstone units were not encountered.



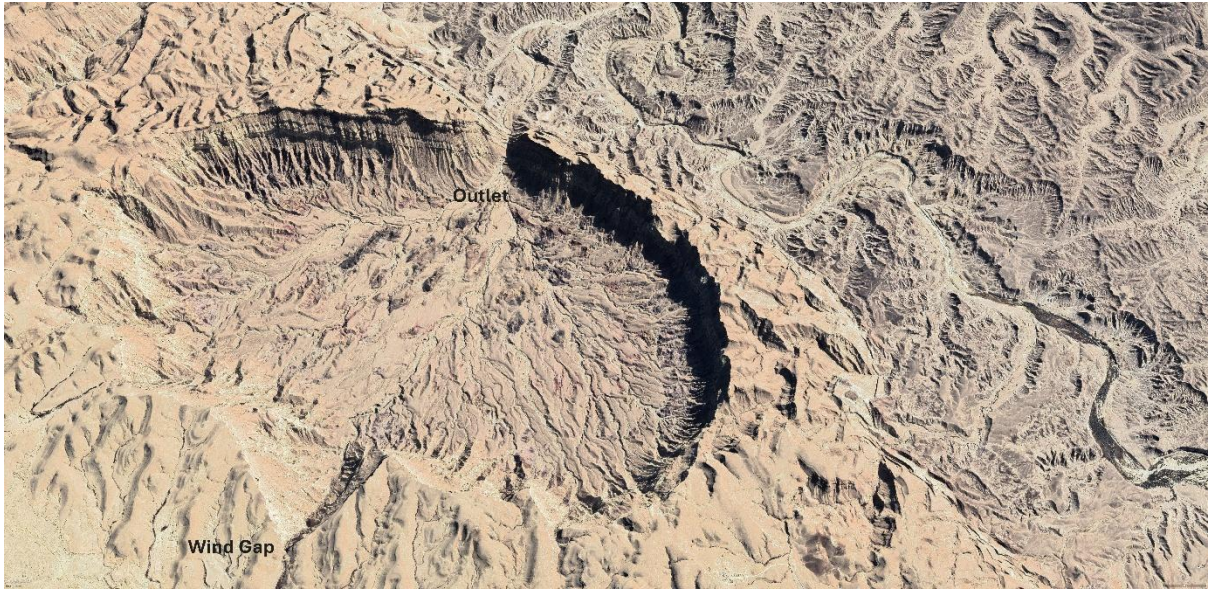
2a. W-E section across the Hatira erosional crater



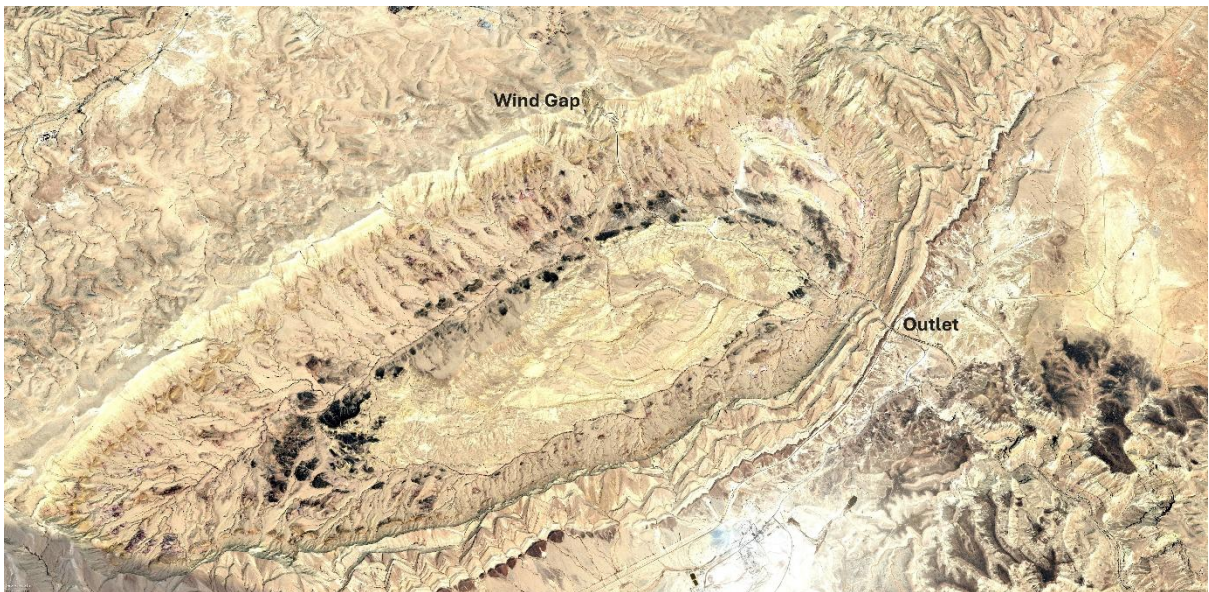
2b. NW-SE section across the Ramon - Mahmal anticlinal axis. Ramon erosional crater, Mt. Ardon



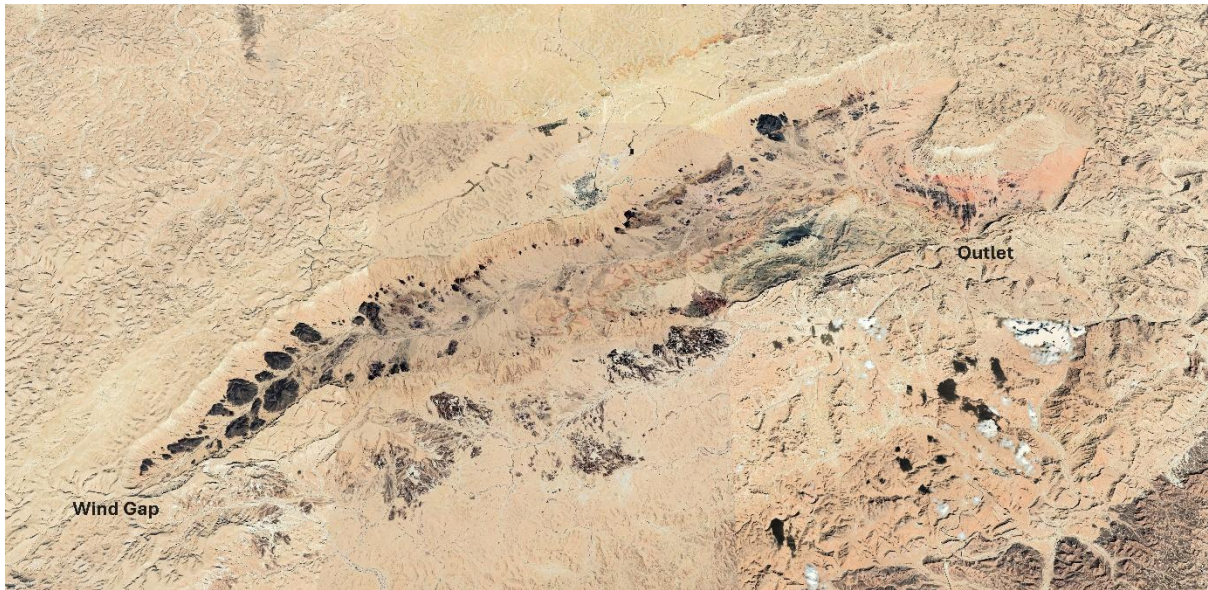
2c. W-E section across the Ramon - Mahmal anticlinal axis. Ramon erosional crater, Mt. Arod



GE1. Hazera Crater. (View eastwards)



GE2. Hatira Crater



GE3. Ramon Crater

Erosional craters could develop in different ways: 1. In association with cross ridges superposed streams. Required prerequisite circumstances are existence of friable beds in the geological section of the folds and friable overlying beds in which incision is taking place. These conditions are met in all three craters of the Negev. 2. By stream incision cutting through ridges slopes or 3. In association with antecedent streams. In the last two options existence of overlying friable beds is not required. Craters could also develop in special environments regardless of the above-mentioned stream regime. In the first option, outlets and inlets or wind gaps abound, whereas in the second only outlets exist.

The role of superposition in interpreting cross ridges streams via water gaps has been discussed since the late 19th century by Davis, (1899a), Johnson, (1931), Von Engel, (1942), Oberlander, (1985) and summarized by Morisawa (1980).

The Negev erosional craters are characterized by having only outlets. The Hatira and Hazera have one outlet; the Ramon has several; none have noticeable inlets or proven wind gaps. Even so, the geological framework does not preclude, but is rather suggestive of the existence of a past superposed stream system.

Previous studies dealing with the Negev craters' mode of formation are in disagreement. Picard (1951, p. 17), found no evidence for antecedent river beds in the north-eastern Negev and therefore suggested gradual expansion and widening of ridge flank's streams, 'ruzes' and 'cluzes', as the process by which the Negev craters were formed. Picard found no signs of superimposed drainage systems either, probably due to scarcity of information available, relating to the wide distribution and thickness of the Miocene soft rock units (Table 2).

Zilberman (2000) defined the northern Negev craters as a unique and rare group characterized by each having a single outlet. His model for the formation of these craters is based on an idea that a peneplain surface developed in the area already in the Oligocene with rivers heading west, from Arabia to the Mediterranean, responsible for truncating the already existing folds, thereby exposing the friable Lower Cretaceous sandstones. Moreover, he speculated on having earlier, Eocene, marine truncation episodes which also cut down through the sandstones. Regional uplift at the Early Miocene resulted in intensified river incision and development of erosional gaps in the folded areas. In principle, according to Zilberman, the craters' framework had already been founded at this point in time.

As stated above, conditions required for the development of erosional craters in superposed stream systems exist in the Negev case. Regional superposition is also alluded to by streams crossing successive ridges in aligned gaps e.g., Nahal Hatira or Nahal Hazera (Fig. 1). Downcutting in existing folds, though without development of craters, also occur to the west of the Negev watershed within the major drainage artery of Nahal Aro'ar. Two river beds, Nahal Revivim and Nahal HaRo'a, tributaries of Nahal Besor, cross the Yeroham-Har Boqer ridge towards the Western Negev. Nahal HaRo'a stream exhibits a course of moderate sinuosity alluding to its superposed drainage origin.

The slope of the Negev craters 'top-of-rim surface' (around 2%) is very similar to that of other crater truncation surfaces formed in superposed stream systems and obviously, is by far gentler than those developed on flanks of folds.

2. Friable lithologies in the folds geological sections

Having friable lithologies in the folds geological sections is an essential for the development of erosional craters; a condition met by the three craters in the Negev where friable lithologies, about 200 meters thick Lower Cretaceous, Kurnub Group (Hatira Formation)

continental and marine sandstones, crop out. Three sandstone and clay units of marine origin are found intercalated in the section and these also are significantly prone to erosive processes. In the Negev folds this sandstone section is overlain by about 400 m thick limestone section of which about 150 m exposed in the craters' walls. Overlying, stratigraphically, are about 300 m and more limestones and chalks of the Senonian Mount Scopus and the Eocene Avedat groups; the Mount Scopus formations, though, were not, apparently, accumulated on top of the folds (Yechieli et al., 1994, Hirsch 1996, Roded 1978, 1996, Avni et al., 2016).

3. Burial of the Negev folds by the friable Hazeva Formation rocks

Establishing a superposed stream system as the cause for the evolution of the craters along the three Negev anticlines, requires development of overlying basins in which friable lithologies are laid, completely burying the formerly folded structures – in the Negev case, it is the overlying fluvial Miocene Hazeva Formation mainly sandstones and clays (Bentor and Vroman, 1951; 1957, Sneh, 1981; Calvo, 2002). It seems, that a 300m thick blanket of the Hazeva Formation would, therefore, be sufficient to enable the process. By the end of the Oligocene and prior to the formation of a depression along the Dead Sea Rift, the Hazeva streams flowed from the regional watershed in Trans-Jordan towards the west (Kolodny 1965; Garfunkel and Horowitz, 1966; Avni 1998; Sneh, 1999). During this stage the drainage courses aligned with the structural configuration in which major transverse streams entrench at anticline low parts and consequent streams flow along synclinal axes. The remnants of such a fluvial system farther west in the Northern Negev can be observed in the Ar'or Valley and its continuation in the Be'er Sheva Valley, where it interfingers with marine deposits (Gvirtzman and Buchbinder, 1969).

Hazeva Formation (Shahaq, Mashaq, Gidron and Rotem members) west of the Sheizaf fault – the western fault of the Rift – is 110m thick in outcrops near Hazeva (Sneh, 1981) and 250 to 500m thick in outcrops and boreholes (Calvo and Bartov, 2001) near Zofar and Zukim.

Within the Rift, in the Arava 1 borehole, T.D. 2738 meters, the lower part of the section can be attributed to the Hazeva Formation, comprising red lateritic shales and red-brown sands overlain by green-grey sands and some gravels. The thickness of this section is still a subject of debate, ranging from 485 meters to 835 meters to 1185 meters according to Neev and

Emery (1967), Calvo (2002), and Zak (1967), respectively. The upper parts of the borehole belong to the Hufeira and younger formations.

In the central Negev near the Ramon Crater, the Hazeva was identified at 700 m above m.s.l. over the Avedat Plateau overlying Eocene beds (Avni et al., 2016) and in tectonic local traps in Nahal Mahmal and in Nahal Teref (Wadi Abu Treife) where more than 230 m Hazeva section, comprising 80 m conglomerates and 150 m of sandstones, clays and gravel is preserved (Bentor and Vroman, 1951). Other preserved exposures outside the Rift area are, in general, only several tens of meters thick, certainly not enough to prove complete burial of the folds. The section in the Yeruham Basin, for example, (Harash, 1967) is 74 m thick with 1.5 m Miocene marine interbed, equivalent of a Miocene, Servallian - Tortonian, marine tongue in the west (Derin and Reiss, 1973). Yet, there are outcrops of basal conglomerates found at higher elevations on the flanks of the Hatira anticline, and about 50 m of red sandstones found on top of the Zohar structure near Arad at 630 m above sea level (Aharoni, 1963). In conclusion, it is reasonable to assume that the thickness of the Hazeva Formation in the Negev, to the west of the Dead Sea Rift, reaches at least several hundred meters, (1700 m according to Zilberman and Calvo, 2013), indicating that the northern and central Negev structures were entirely covered until late in the Tortonian. That being so, an incised superposed stream system is therefore the preferred explanation for the formation of the cross ridges streams and development of the erosional craters.

Significant tectonic evolution of the Dead Sea Rift in the Upper Miocene resulted in the establishment of a new western regional watershed (Extending from Arad to Har Boqer), altering the drainage direction, from west to east and eradicating former stream tracks. All three craters are located on the east side of the newly established watershed. Most of the newly redeposited sediments from this event, mainly sands and gravel comprising the Hufeira Formation and Arava Conglomerate (Calvo, 2002; Horowitz, 2001), were laid in the Rift depression building thick sedimentary sequences.

It should be added that exposures of the Hazeva Formation were not observed from anywhere within the craters. A 'lonely' outcrop of Neogene Conglomerate, marked Nc or Nh on maps, is exposed in a hill, 70 m high, at the floor of the Hatira Crater (Neev, 1960); actually, it is a conglomerate, not part of the Hazeva Formation but rather a younger one, Plio-Pleistocene according to Issar (1983), just like the conglomerate strip outside the crater which surrounds the Rotem Basin on its western side.

4. Wind gaps - 'Inlets by conjecture'

The northwestern rim in all three craters does display breached topographic gaps, however, since they are of no more than a few tens of meters depth, they are not considered wind gaps of superposed stream systems. Still, in both the Hatira and Hazera craters, there is one gap which is deeper than the others. In several sites, Hazeva sediments bottom these gaps; they are horizontally laid or even dip toward the synclines away from the craters. In both Hatira and Hazera craters, opposite their outlets, the crater escarpment has been retreating relatively more rapidly, about 500 to 1000 m from its front, forming deep funnel-like gorges reflecting the migration northwestwards of the Kurnub - Judea contact, an erosional process occurring contemporaneously with the incision created by the, apparent, main crossing stream of the anticline. These gorges are not wind gaps by themselves but rather hinting at old eradicated inlets, referred to, herein, as 'inlets by conjecture'.

There is no sign of an inlet into the Ramon Crater along its northwest rim. Yet, during the Miocene, the Ramon area and south of it, was crossed by the Hazeva Formation fluvial streams flowing from the east side of the DSF, just as was deduced for the northern Negev, leaving a thick blanket of channel and overbank deposits over the Oligocene denudation surface (Avni, 2001). In the Ramon case, because of its more southern geographic position, the streams flowed towards Wadi El Arish in the Sinai. Development of the depression along the DSF resulted in the capturing of the drainage courses with streams flowing northeast, the direction of the present day Nahal Ramon, towards the Dead Sea depocenter. Nahal Loz flowed northeastwards and was probably connected to Nahal Ramon. The western tip of Nahal Ramon is thus an 'inlet by conjecture'. This route, along the crest of the Ramon paleo-ridge, is also the one with minimum depth to the top of the Hatira Formation sandstones as well as where the minimum thickness of the Hazeva blanket is. The Ma'ale Arod wind gap is, probably, part of the same drainage system. At its outlet from the crater, Nahal Ramon combined with Nahal Neqarot, has a semi meandering pattern crossing the major Ramon fault, regardless of its existence (GE3a). This being so might suggest a remnant of an old superposed stream.



GE3a. Ramon Crater, Neqarot outlet

5. Stages in the evolution of the Negev craters

Analysis of the Negev craters yields four stages (Fig. 3):

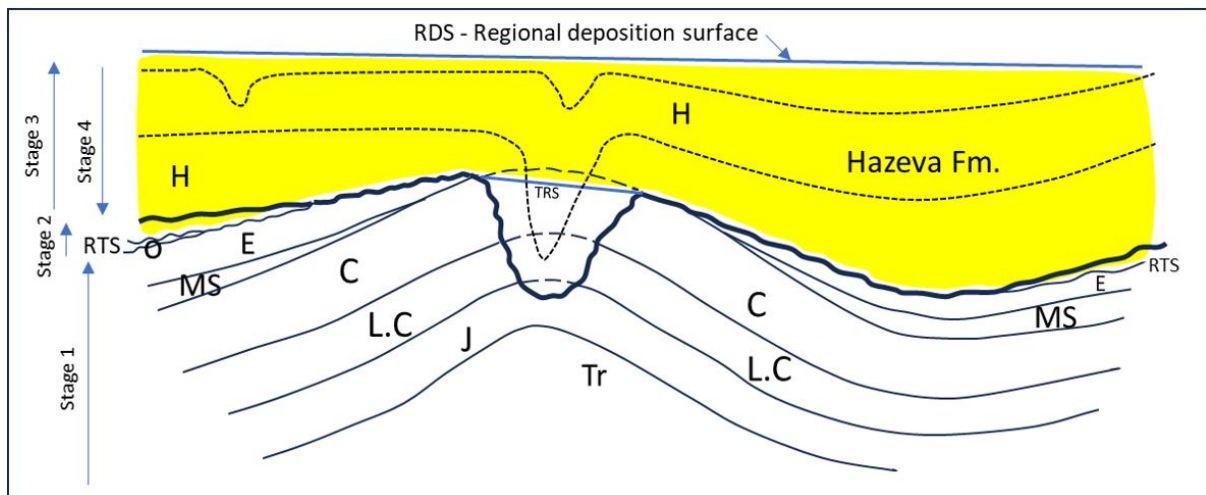


Fig. 3. Stages in the development of the Negev craters (Schematic presentation). Tr – Triassic; J – Jurassic; LC - Lower Cretaceous; C – Albian-Turonian; MS – Mount Scopus; E – Eocene; O - Oligocene; H- Hazeva Formation; RTS – Oligocene-Early Miocene regional denudation surfaces; RDS - Regional deposition surface; TRS - Top-of-rim surface. Thick black line – Present day surface.

Stage 1: Folding phase begins by the end of the Turonian with unconformities in the Senonian and Paleocene, observed in each of the Negev folds. Marine sedimentation continues throughout the Eocene and in the Oligocene. In late Oligocene denudation conditions prevailed. There is no evidence of fluvial cross-ridge streams during folding.

Stage 2: The Pre-Rift erosion phase. Denudation continues until the middle of the Early Miocene (approximately 20 million years ago) in a structurally dependent drainage system and strata are ripped off from the top of structures. However, Hatira Formation sandstone units are not encountered (see Fig. 2). Streams flow from the east side of the Dead Sea Fault (DSF) westward towards the Mediterranean through major channels such as Rotem Junction and Aro'ar ancient gaps, following the structural pattern. Consequent streams follow the synclinal valleys; the Be'er Sheva Canyon develops in the west.

Stage 3: Depositional phase, possibly continuing until late in the Tortonian, approximately 7 million years ago. The Hazeva Formation fluvio-lacustrine beds were laid down first, overlain by fluvial beds, thereby burying exposed structures and forming a depositional plane surface subjected to renewed degradation. Occurrence of tectonic pulses in the Dead Sea Rift area, brought about thick sequences of the Hazeva, although a morphological depression has not yet formed. Marine sediments of the Ziqlag Formation were deposited in the northwestern regions of the Negev, including the Be'er Sheva Canyon, as the transgression invaded towards Yeruham.

Stage 4: The main phase of formation of the erosional craters. Once a major tectonic activity starts along the Dead Sea Fault, the incision of the Hazeva floodplain channels, whether meandering or not, begins. As long as the channels penetrate through the Judea hard rocks, the incised streams are being entrapped, but once they reach the friable Hatira sandstones, fast widening of the fluvial system occurs thus changing the system's pattern. The tectonic activity lasted throughout the middle of the Tortonian, Upper Miocene and onward, while forming a morphological depression on the east side of the Sheizaf-Zofar fault. Folds on the east side of the Negev descend towards the Rift, creating a new watershed line stretching from Arad to Har Boqer, resulting in two drainage systems, one towards the Rift and another towards the Mediterranean Sea; actually, two superimposed systems. The erosion initially targets the Miocene clastic sediments and redeposits them in the Rift (Hufeira and Arava formations). Subsequently, during the Messinian and the Plio-Pleistocene, older rocks down to Triassic formations are incised as well, forming cross-ridge gaps and erosional craters.

6. Superposed stream system in Nahal Soreq to the north of the Negev

Another relevant fluvial superimposed system, though lacking an erosional crater (Structural as well as lithostratigraphical conditions are not suitable), is, that of Nahal Soreq, which crosses the Judea Mountains to the north of the Northern Negev. Topographic cross-sections perpendicular to the Soreq valley reveal a distinct morphological, intermediate step, called herein Har Pitulim surface (Figs. 4; 4a).

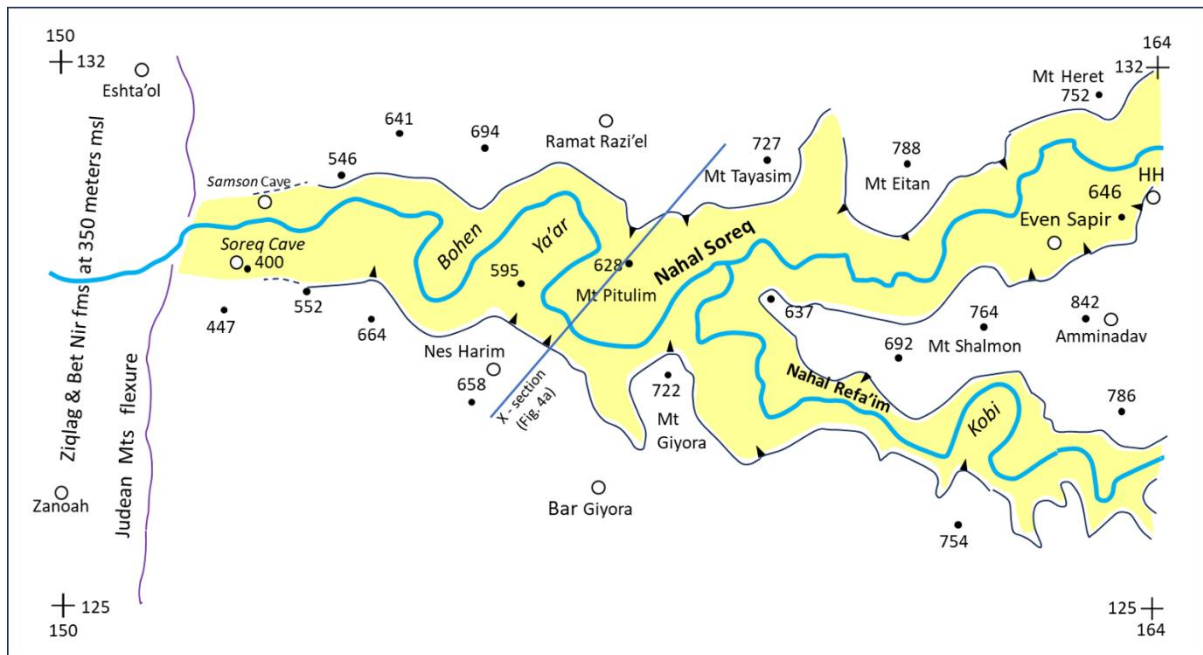


Fig. 4. Nahal Soreq superposed stream system. Mt Pitulim surface shown in yellow color. Black triangles - morphological nick-points. Black dots – topographic elevations above msl. Small circles – places. HH – Hadassa Hospital, Jerusalem. Attached: Nes Harim – Mt Tayasim topographic cross section (Fig. 4a) position.

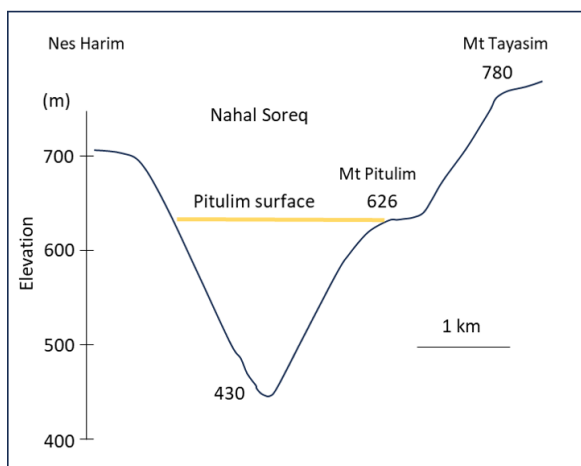


Fig. 4a. Nes Harim – Mt Tayasim topographic cross section

It extends two kilometers wide and sits 150-250 meters below the mountain top level. In the eastern region of the Soreq Valley, in a cross section from Mount Shalmon to Kobi Spur the step is 620 meters above sea level and about 580 meters at the Ya'ar and Bohem spurs to the west, gradually sloping westward. This morphological level is suggestive of a pre-Rift river that flowed from Transjordan, taking a route through a structural saddle in the Jerusalem area between the Ramallah-Sho'eva and Hebron anticlinal highs. This phase likely occurred early in the Middle Miocene and was followed by deposition of meandering channel and overbank sediments, which no longer exist. At that time, apparently Serravallian - Tortonian, the Hazeva Formation was laid in the Negev. Following, uplift of the Judean mountains triggered downward incision and stabilization of the meanders in the Upper Miocene, mainly Messinian and onward. Incision depths exceed 200 meters. It is assumed that the channel and fine overbank sediments, were re-deposited in the Bet Nir Conglomerate, which overlies the Miocene marine Ziqlag Formation, to the west of the Judean mountains. This last stage can be compared to the one during which the Negev erosional craters were established. During the long period the 'Hazeva' equivalent floodplain existed over the intermediate Pitulim Surface, local groundwater level was obviously high which contributed to the development of karstic caves in the underlying rocks. Two of the well-known Soreq and Samson caves (400m msl) are located straight below the Pitulim Surface and indeed recent investigation (Chaldekas et al., 2022) determined that they were developed during a long period of high groundwater level from 14 Ma to 6.1 Ma.

7. Conclusions

The Negev erosional craters, like most erosional craters in folded belts around the globe, have developed in association with cross-ridges streams. During the Messinian and onwards and in response to the formation of a depression along the Dead Sea Rift and an uplift of its shoulders, a superposed stream system was established. The Middle and Upper Miocene (Langhian – Tortonian) highly friable sandstones and clays that covered the Negev folds underwent a stage of incision down into Lower Cretaceous highly erodible sandstones which eventually developed into erosional craters.

8. Appendix: Erosional craters worldwide.

Introduction

Erosional craters are elongated to roughly circular, topographic depressions with steep slopes. They are widely observed in folding belts worldwide e.g. in the Appalachians, Rockies, Jura Mountains, Atlas Mountains, in folds of the Syrian Arc, Zagros Mountains and in the MacDonnell and Flinders ranges, Australia, displaying a wide range of shapes and forms. While they typically have a classical bowl shape, they can also take on various other, sometimes quite bizarre forms such as spindles, cigar-like forms etc., depending on the structural configurations.

The craters can develop along the crests of anticlines, as well as in synclines, domes, and fault-controlled areas. The folds may be symmetric or asymmetric and the crater's floor can either be flat or incised. In addition to the structural factors, the morphology of erosional craters is primarily influenced by the type, thickness, and arrangement of less and more friable beds within the geological section. Their size ranges from several square kilometers to several hundred square kilometers. Small and "mini" craters lack extensive valley floors.

The number of erosional craters having 'perfect' or 'nearly perfect' shapes is relatively small (Table 1, T1 – T44, presents basic data: location, size, relief). Some hold value for their scenic beauty as well. Clearly, there are hundreds more, partially 'preserved', 'imperfect' craters that have been affected by either tectonic processes or erosion and could also be useful for the scientific examination.

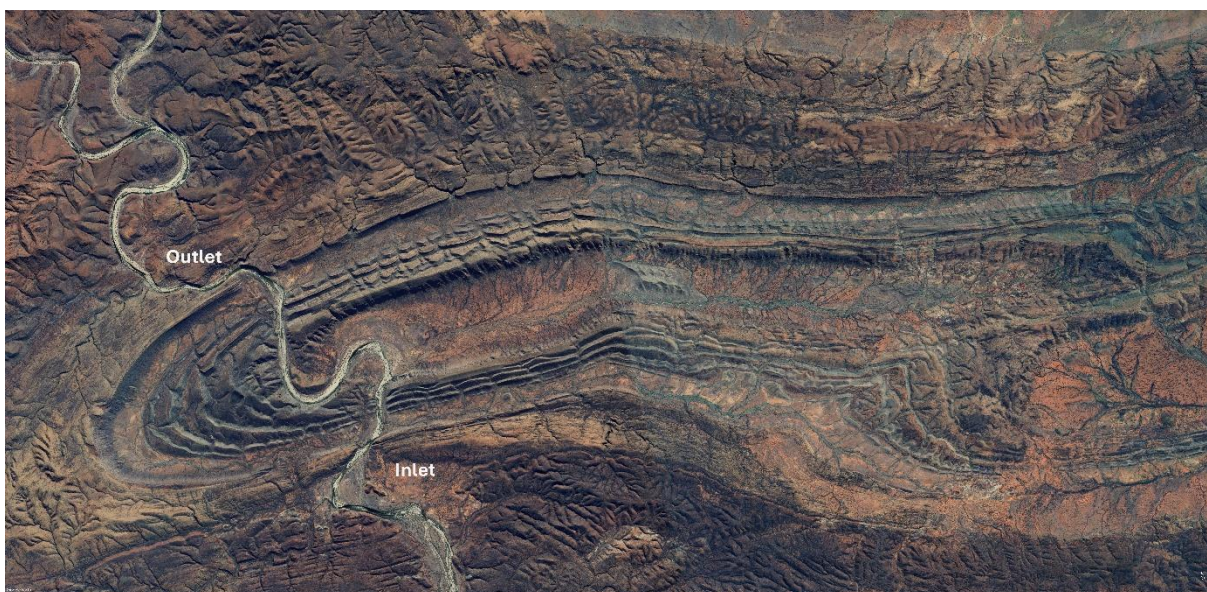
Sweeping through Google-Earth (**GE**) images displaying a diverse range of erosional craters, worldwide, lends itself to analysis and better understanding of their mode of formation, be it development in association with cross ridges streams, be it restricted to flanks of structures or relating to other geological environments. Cross ridges water gaps could develop in a superposed stream system in the way incised meanders are formed, by capture of streams or as antecedent streams.

In most cases, erosional craters are associated with incised, cross ridges streams, linear, meandering or semi-meandering, a kind of geomorphic features referred to as 'breached valleys' or 'breached anticlines' (Von Engeln, 1942), suggesting a superposed drainage origin. Once a stream crosses a fold encountering friable beds, incision takes place more intensively along its course as well as along the fold axis thus expanding it to form a crater.

The majority of erosional craters have both inlet and outlet water gaps. They are usually the result of regional superimposition, unless fold crossing occurred before or during the folding phase; the incision of crossing streams, is not necessarily revelatory of the antecedent scenario. The role of superposition in interpreting cross ridges streams via water gaps has been discussed since the late 19th century by Davis, (1899a), Johnson, (1931), Von Engel, (1942), Oberlander, (1985) and summarized by Morisawa (1980).

Craters that illustrate superposition

Examples that illustrate superposition include Owen Springs Crater in Australia (T41), characterized by its winding Hugh River course, and the Finke River Crater with its tortuous incised meander (GE4, T42), the Pir Zinda Sahib Crater in Pakistan (GE5, T35) and the Everett - Bedford Crater (T1) in Pennsylvania, along with its Juniata meandering river and the small Oval Crater (T2) in one of many parallel ridges traversed by the Susquehanna River and the Lavelanet Crater (T10) in France, an 'imperfect' crater, which is crossed by two rivers, Le Touyre and L'Hers. Even in the rugged terrain of the Caucasus, the Karakoyus River cuts its way across successive anticlinal ridges where the rounded Kurmi Crater, Dagestan, Russia (T38) has been developed. Machtesh Inlioua (GE6, T15), Morocco, is a double crater 700 square kms in size, carved in an anticline structure. Proterozoic rocks are exposed on its floor, overlain by Cambrian strata, building the crater's rim. Several streams cross the crater.



GE4. Finke River Crater



GE5. Pir Zinda Sahib Crater (View northwestwards)



GE6. Machtsh Inlioua Crater

All of the above craters develop in anticlinal structures. However, craters are also common in synclinal morphological ridges. Likewise, the inlet and outlet gaps are indicative of the stratigraphic superposition. In Iran, the Maroo Crater (GE7, T27), situated in a syncline, is intersected by incised semi-meandering river beds inside and outside the crater limits, independent of the structural orientation. Similar features are observed in the Tisslite Ait Douchen Crater in Morocco (T14), a nested "craters within craters" with three wide cuestas in the inner side, in the shallow Bni Ykhlef Crater (T16) and in the Talbanine Crater in

Morocco (GE8, T17). Bela, kidney shaped, synclinal crater, Pakistan, (T34) is a huge, 1300 square kms in size, crossed by the Hingol River which displays a course of moderate sinuosity within the crater and a meandering course outside.



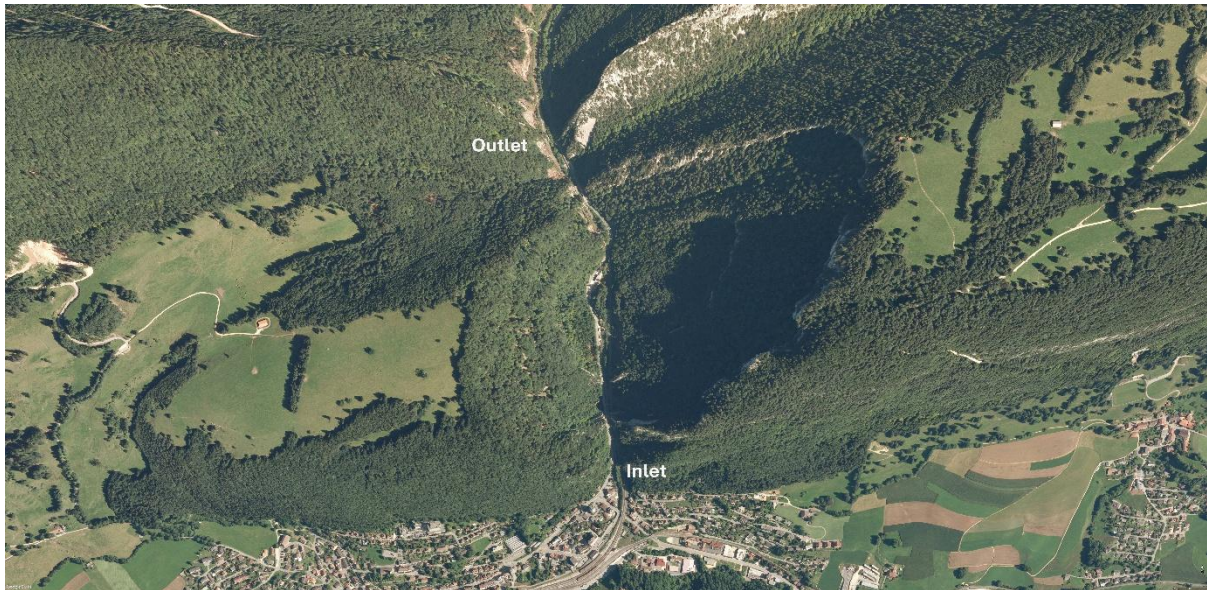
GE7. Maroo Crater



GE8. Talbanine Crater

Small size erosional craters are actually water gaps crossing narrow anticlinal ridges, and in places where the beds are not highly friable, their widening is limited. Generally, they lack a flat floor at all. The Karkheh River, Iran, crosses the Zagros folded belt via many water gaps

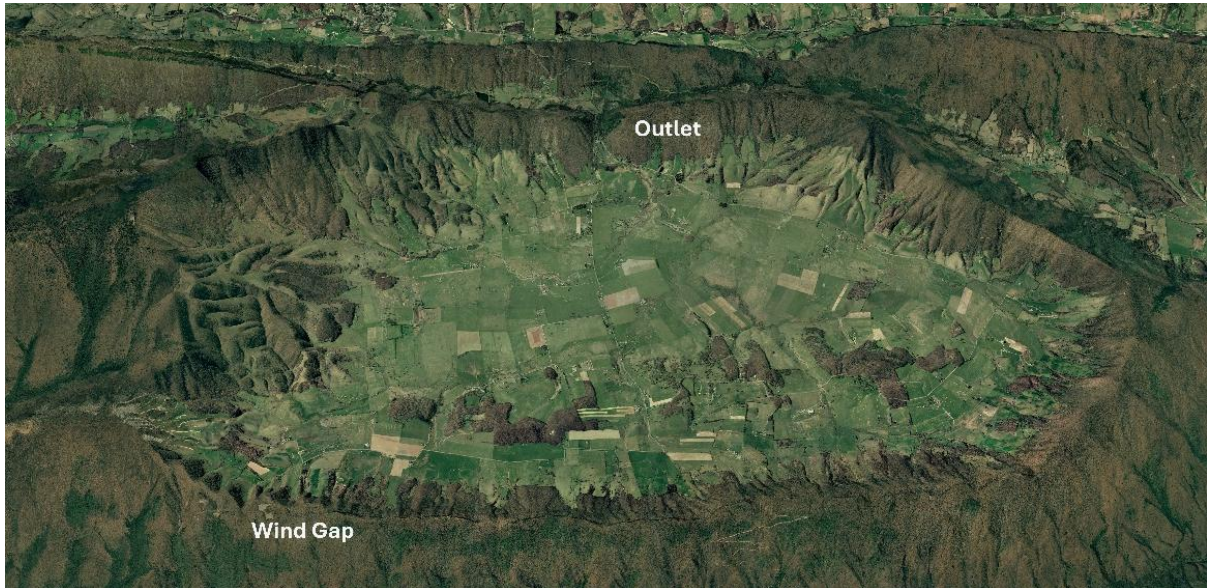
among which some, like the one at Tang-e Leylam, Lorestan Iran, (T29), have developed into erosional craters. Likewise, the Zohreh River crosses the Zagros anticlinal ridges exhibiting an erosional crater near Hajj Qalandar (T31). Both craters and others like the Nowdan Crater, Khuzestan Iran (T28) and Dishmok Crater (T30), Iran or the Switzerland Jura Mountains 'mini' erosional craters of the La Birse River, Court Crater (T12) and Moutier Crater (GE9, T13) are incised at the plunge of anticlinal ridges.



GE9. Moutiers Crater

Many erosional craters lack inlets and instead exhibit wind gaps, suggesting the presence of abandoned inlets. However, interpreting a wind gap can be challenging in many cases. Certain physical characteristics, such as the position in relation to the outlet, can facilitate in the interpretation of wind gaps. In Burkes Garden Crater, Virginia (GE10, T4), the Walker Trail represents a wind gap saddle located approximately 100 meters above the crater floor and up to 300 meters below the rim elevation. Similarly, in the Borregas Crater, Coahuila, Mexico (GE11, T8), the Puerto Borregas wind gap saddle is situated about 100 meters higher than the crater floor and approximately 200 meters below the rim. In a crater located west of Salinas Victoria, NL Mexico (T9), a topographic saddle suggestive of a wind gap can be found at the southeast corner. It is positioned around 200 meters higher than the crater floor and about 300 meters below the rim. Wind gaps were observed in two synclinal craters as well: The Tassoufante Crater, Morocco (T18) has a shallow 100 m deep wind gap, 50 m above the crater's floor. Likewise, the Black Gap, Wilpena Pound Crater, Flinders Range,

Australia (T43) is a 200 m deep wind gap about 100 m above the Pound surface. The Pound is drained northward via the 300 m deep Bridle water gap. In the Qadzi Kalay (Urgun) synclinal crater, Afghanistan (T37), the observed wind-gap(?) is not clearly defined since it is very shallow, about 80 m below the crater's rim.



GE10. Burkes Garden Crater (View northwestwards)



GE11. Borregas Crater (View northeastwards)

A more complex example is the Ormara Crater (T36) in Pakistan (Baluchistan), which faces the Indian Ocean. This synclinal (possibly asymmetric) crater exhibits physiographic

asymmetry, with the north rim relief measuring 850 meters and the south rim only 60 meters. It features one outlet and one wind gap located 500 meters below the crest of the north rim. Presumably, the erosion of the southern rim of the crater occurred predominantly due to post-folding tectonic events and was influenced by Quaternary sea-level fluctuations.

Craters developing on the flanks of ridges

The main group of erosional craters, not associated with cross ridges streams, includes craters, generally having only outlets, developing on the flanks of ridges. Over time, once incised into friable beds, these craters may widen and occupy areas on top of ridges along their axis, as well. This process, however, cannot explain crossing of successive ridges in aligned gaps. Erosional craters developing and limited to the flanks of anticlines, i.e. have no relation to cross streams, are extremely less common. The Sinjar Crater, Iraq (T26), for example, is a flank crater and so are the craters in Gebel Hallal, Sinai Egypt (T21), the Chellala in Algeria (GE12, T44) and the tiny mini crater of Har Arif, Israel (T25). Other flank craters with no discernible inlet are questionable, e.g. at Gex (T11), France, or at the Buffalo Mills Crater (T3), in the Appalachians, Pennsylvania. The Abdan and Baghan, Bushehr, Iran, opposing mini flank craters (T32), demonstrate an initial stage of development.



GE12. Chellala Crater

The slope of the craters top-of-rim surface is quite high, e.g. at Gebel Sinjar, Iraq (12%), at Gebel Hallal, Sinai (9%) or at Har Arif, Israel (25%).

Other craters develop without any relation to cross ridge fluvial systems

Erosional craters can, obviously, develop without any relation to cross ridge fluvial systems and as such they are not indicative of regional stratigraphic superimposition. A case in point are the synclinal valleys with surrounding steep rims and friable overlying rocks having no inlets or wind gaps, e.g., in the El Haouita Crater, Algeria (T19). Dome structure craters, when not intersected by a river bed, obviously lack inlets (See Devils Pocket Crater, (T7), Montana, with two outlets, Lobeck, 1939).

In the Sahara Desert, where extremely arid conditions prevail and the landscape is highly mature with salt pans and deflation surfaces - an endorheic basin - erosional craters relief is a few meters only. In such an environment, craters may even lack both inlet and outlet! e.g. in a crater carved in a dome structure, 140 km south of In Salah, Algeria, (GE13, T20).



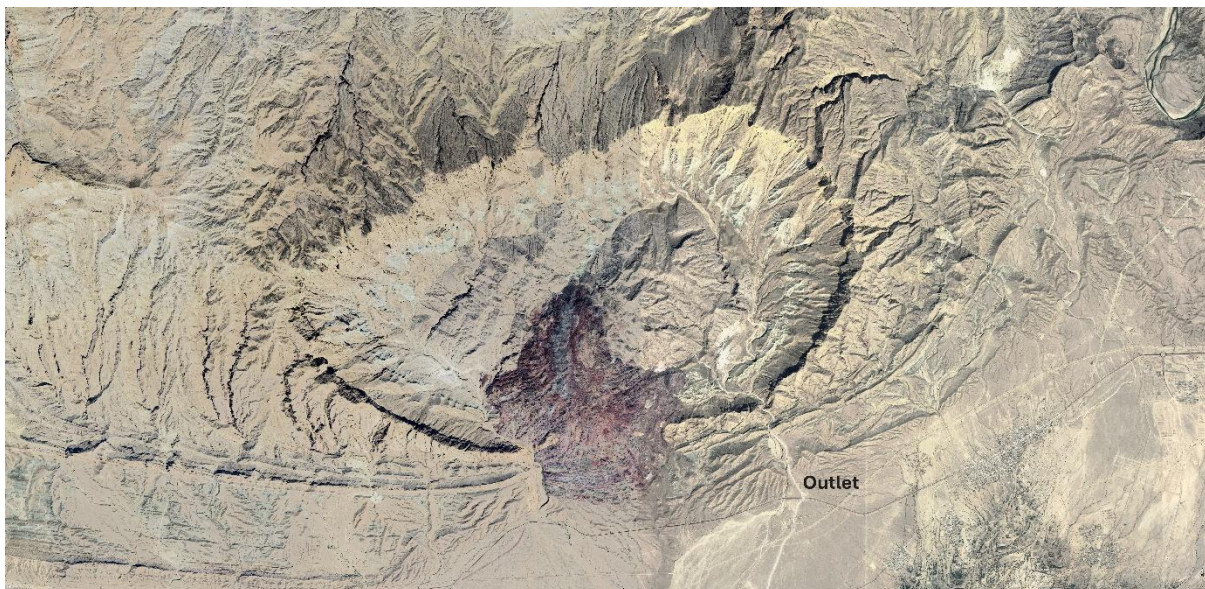
GE13. In Salah Crater

Craters associated with presence of salt beds

The Sakon Nakhon Crater, Thailand (T39) and the nearby Kalasin, Kuchinarai Crater (T40), are examples of erosional craters with no cross streams, inlets or visible wind gaps; they

likely had inlets that have been eroded away. They are described by Furukawa and Pitchai (1989), exposing the Late Jurassic-Barremian Phra Kardung marls, which are prone to intensive weathering, and the overlying Phra Wihan sandstones, which are more resistant. These formations are overlain by the Aptian to Campanian Maha Sarakham fine clastics, alternating with salt beds, and the Phu Thok sandstones and clays (Hitoshi et al., 2010), which are exposed on the outer flanks of the crater. The dissolution of the Maha Sarakham salt rocks involving collapsing processes (see Maret and Coe, 1960 with respect to the Sinbad Valley, T6, and Paradox craters, Colorado, T5) has created ideal conditions for the incision of younger river beds, leading to the establishment of a superposed stream system and formation of the craters.

In southern Iran dozens of salt diapirs breach the surface forming 'dissolution' collapse craters where they are surrounded by much more resistant rocks. The craters are not positioned in relation to the host folds, lack inlets, and exhibit salt 'flows' through outlets, resembling alpine glaciers, with crevasse-like pattern at the salt flow front as observed in the Anguran salt dome, Iran (GE14, T33), in the Herang Salt Dome, and near the Moseyjed Village; none of them relates to cross ridge stream system. Near El Abiodh Sidi Cheikh, Algeria, a crater was also likely formed through a collapsed process following salt diapir dissolution.



GE14. Anguran Crater. Dark colored area – salt rock.

Concluding remark

The majority of erosional craters in folded structures, having both inlets and outlets, develop in association with superposed cross ridges streams. In certain cases, though, inlets are absent but wind gaps can still be detected. Erosional craters, limited to the flanks of folds, have only outlets and are relatively uncommon.

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תקציר

מכתשי הנגב, כמו מרבית המכתשים הארוזיביים הידועים מגושי קמטים בעולם, התפתחו כחלק ממערכות ניקוז רוכבות. רובן מאופיינות בנחלים חוצי רכסים; בחלקן אפשר לאתר כניסת נחלים מרומזת בלבד. במשך המסיניין ואילך ובתגובה להתפתחות בקע ים המלח פעלה אף בנגב מערכת ניקוז רוכבת. בשלב ההתרוממות הטקטונית של הנגב, אבני החול והחרסיות הרכים של תצורת הצבה שכיסו את הקמטים במיוקן התיכון והעליון, נחדרו בקלות על ידי הנחלים. הללו המשיכו בחדירתם כלפי מטה באפיקים כלואים דרך הסלעים הקשים של חבורת יהודה עד להגעתם לאבני החול, המתפוררות בקלות יחסית, של תצורת חתירה מהקרתיקון התחתון. בתנאים אלה מתאפשרת הרחבה לטרלית של השטח הארוזיבי עד להתפתחות המכתשים.



משרד האנרגיה
המכון הגיאולוגי

התפתחות המכתשים הארוזיביים בנגב במערכות ניקוז 'רוכבות'

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עמיחי סנה